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# TELECOMMUNICATION APPLICATIONS OF MILLIMETER WAVES

P. DuPuis



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16. Abstract

This paper is a review of potential applications of millimeter waves, which first appeared available for high capacity transmission by circular waveguide. Despite considerable effort devoted to this application, it did not result in an operational system. Today new advances in solid state technology and innovative design can substantially decrease the costs of millimetric systems and allow the new requirements of local networks and mobile communications to be met.

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# TELECOMMUNICATION APPLICATIONS OF MILLIMETER WAVES

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## 1. Introduction

The subject of millimeter wave application is not new. The engineers who conceive millimeter components and subassemblies have long asked transmission system engineers for potential applications of millimeter technology. /35*

The responses of the latter have always been cautious if not evasive. It has long been thought that the circular waveguide would be the vehicle of millimeter transmission in the civilian area, but waveguides have long been ahead of their time, and the hopes placed on them have not been implemented by orders for operational communications.

The situation has evolved today, mainly because the bands of the centimeter range are all occupied or at least assigned in both microwave transmission and space transmission, while the development of the telecommunications network has caused the appearance of new potential applications in subscriber networks and mobile communications.

Also, to attempt to tabulate a set of applications of millimeter technology, both guided transmission and microwave transmission, as well as space transmission and mobile communications which have been studied or are being studied must be described.

*Numbers in the margin indicate pagination in the foreign text.

Article from Journee d'Etudes SEE, 5 December 1980.

## 2. Transmission by Circular Waveguide

### 2.1. Transmission Carrier

The guided transmission of electromagnetic waves has been the subject of studies since the 1930s. It quickly developed that only the TE01 mode, guided in a circular oversized conduit, could permit long distance transmission. To maintain reasonable guide dimensions, i.e., an inside diameter of 50 to 60 millimeters, it was thus necessary to be in the millimeter wave range.

This was a new frequency area in the 1950s and even the 1960s beyond customary frequencies, in a way the new frontier of microwaves. Components were scarce and measurement techniques frequently simple. Indeed, the prospects were very promising, since transmission losses of less than 3 dB per kilometer were expected in a band of several tens of GHz.

Research is oriented in different directions. The guide itself first had to be perfected. Different options could be considered. The deposition of a film of dielectric material of a well-selected thickness and dielectric constant permits compensation for the degeneration between the useful TE01 mode and the stray TM11 mode and to thus decrease the coupling due to imperfections of the guide. This option was chosen in the United States. The use of a helicoidal circular waveguide was preferred in France and Great Britain. The wall is then composed of an insulated copper wire wound in contiguous turns in a helix, which permits elimination of the transverse magnetic modes.

In addition, any curvature of the guide causes further attenuation. To avoid any bending due to force exerted by the sun in a trench, the guide can be protected by putting it in a steel conduit. Such protection, the option chosen in the United States in particular, has permitted transmission losses of less than 1 dB per kilometer to be obtained in a 70 GHz frequency band.

In France, in order to limit installation costs, it was preferred not to use such a steel conduit and to install an electrical shield outside the copper turns to reduce the effect of curvatures. Fifteen kilometers of guide made according to this principle were thus buried near Lannion in 1973. The losses obtained were relatively high because of lack of rigidity of the casing. A major effort was subsequently made to simplify the guide fabrication process. In addition, the inside diameter was increased from 50 to 60 millimeters, and a steel sheath was installed. The transmission losses of this new guide, measured over 5 kilometers, are 1.5 dB per kilometer in a 35 GHz band. /36

## 2.2. Transmission and Receiving Equipment

The perfection of millimeter subassemblies for circular guide transmission has permitted considerable progress to be made in millimeter technology, in particular at the beginning of the 1970s.

Millimeter channel connection equipment had to be made first. Semicircular duplexers had to be completed to separate the transmitted signals from the received signals and to divide the frequency bands into subbands of approximately 6 GHz. This type of duplexer includes two semicircular guide couplers with multiple coupling openings. Two high pass type cutoff filters were inserted between the two couplers. The channel relay circuits are made up, as for microwave beams, of circulators and cavity filters. Major progress associated with machining methods in particular, have permitted low loss, wide band couplers and circulators, as well as temperature stable cavities to be made up to 50 GHz.

In addition, the appearance of semiconductors (varactor, Schottky diode, Gunn diode and avalanche diode, etc.) has permitted the completion of transmission and receiving mixers, cavity stabilized oscillators, transmission amplifiers, etc.

In the final phase of industrial development of the waveguide

transmission system at a rate of 560 Mbit/s per channel, microelectronic mixers were made of transfer chip diodes on the microstrip line of a guide-microstrip transition. The use of linear avalanche diode amplifiers has permitted the transmission power to be raised to more than 100 mW.

## 2.3. Evolution of High Capacity Systems

Large efforts made on waveguide transmission resulted in experimental communications with industrial prototypes in four countries (Japan, United States, Great Britain and France) [1]. A balance sheet of these studies was drawn in 1976, during the last IEE conference on millimeter waveguides in London [2]. It then was proved that the guide transmission technique was completely mastered at this time.

But waveguide transmission has not gone from the experimental stage to that of operation, even in Great Britain, where a 125 kilometer operational link was programmed then cancelled. In a way, the development of the waveguide has anticipated the needs of the telecommunications network. On the one hand, as long as the communications to be transmitted remain telephone communications, the transmission needs will be covered in large part by coaxial and microwave networks.

On the other hand, in order to ensure good routing safety, it is not possible to concentrate the traffic of the major trunks in a single transmission carrier such as waveguides.

Under these conditions, the installation of communications with a capacity of more than 10 Gbit/s will only occur at the time when the network has to carry communications with live images. At this time, the waveguide will be in competition with both large diameter coaxial and optical fibers. Table 1 shows the state of progress of these different techniques. In France, this takes account of the results obtained in the study stage and not the operation stage, which generally occurs several years later.

TABLE 1.

| | a Année d'expérimentation | b Débit par canal ou par « paire » Mbit/s | c Distance entre émetteur et recepteur km | d Facteur de mérite Gbit/s × km |
|---|---|---|---|---|
| Coaxial 2,6-9,5 mm | 1975 | 140 | 4 | 0,6 |
| | 1979 | 560 | 1,5 | 0,9 |
| e Guide d'ondes 50 mm | 1970 | 220 | 15 | 3 |
| 50 mm | 1974 | 560 | 20 | 11 |
| 60 mm | 1977 | 560 | 35 | 20 |
| f Fibre optique | | | | |
| multimode | 1974 | 34 | 6 | 0,2 |
| multimode 0,8 µm | 1977 | 140 | 8 | 1,1 |
| monomode 1,3 µm | 1981 | 140 | 50 | 7 |

Key: a. Year of experiment
b. Rate per channel or by "pair," Mbit/s
c. Distance between transmitter and receiver, km
d. Factor of merit, Gbit/s x km
e. Waveguide
f. Optical fiber

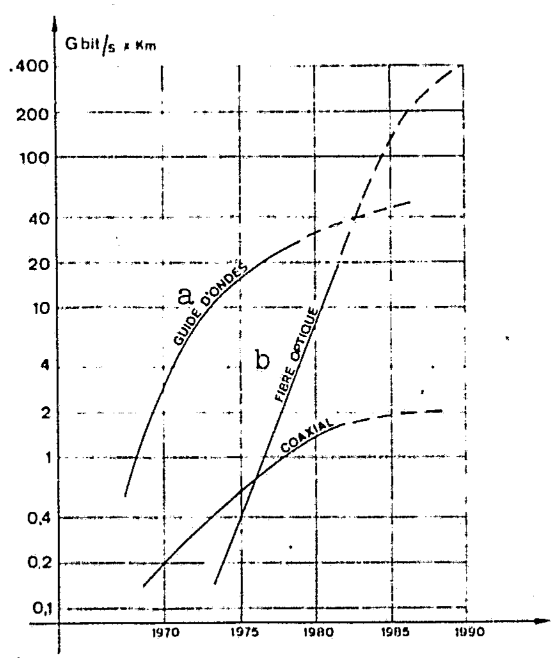


Fig. 1. Factor of merit for high capacity systems.

Key: a. Waveguide
b. Optical fiber

It can be considered that the product of the numerical rate times the distance between repeaters is a factor of merit for high capacity interurban transmission systems. This factor of merit becomes economically significant when the cost of the infrastructure (structures, power, line protection, etc.) and of installation become important in the total cost of the system.

The chronological evolution of this factor of merit is shown in Fig. 1. The performance of a transmission technique first evolves very quickly, both due to the skill acquired in the transmission carrier (the transition of multimode fibers to monomode fibers for example) and by the appearance of new components which per- /37

mit higher transmission rates in particular.

The technique then stabilizes, as is the actual case of coaxial transmission, where it should not exceed 1.5 Gbit/s x km. For the circular waveguide, if studies were continued today, the performance of the transmission carrier undoubtedly would evolve little. On the other hand, the rate per channel would be increased to at least 1200 Mbit/s. It can be estimated that the ceiling of the factor of merit of the waveguides would be approximately 50 Gbit/s x km.

Figure 1 indicates a divergence between the developments of the waveguide and optical fiber in high capacity transmission, which can be calculated at about ten years. The possibilities of optical fibers are clearly better known today than five years ago. It is even possible now to predict that their factor of merit eventually will reach several hundred Gbit/s x km.

## 3. Microwave Transmission

### 3.1. Microwave Beams

Microwave beams have been developed mainly between 2 and 12 GHz. A heavy infrastructure which it is difficult to expand has been installed in France. More than 600 masts and towers have been built for long distance networks, and the length of the corresponding microwave jumps is large and quite uniform, since it generally is between 35 and 65 kilometers. Moreover, it can be noted that this option, which was chosen in the 1950s, was not evident for long jumps in the beginning. A.G. Clavier, the French engineer who brought into being at 2 GHz in 1930 between Calais and Dover the first microwave communications in the world, wrote the following lines in 1946 [3].

"Therefore, it now can be foreseen that microwave cables will have major use in telephone networks, in all cases where the cable sections have to be installed under arms of the sea, a large river, in a mountainous region or where access is difficult in particular. Therefore, there is no doubt that the construction of a large number

of towers to support the transmission and receiving horns of the relay stations will soon be seen. Either high towers where, except for telephone equipment proper, services which likewise call for centimeter waves and are used as aerial navigation aids for example will be concentrated, or microwave cables which use the shortest wavelengths permitted by the laws of propagation, which will result in short towers and infrastructures which are similar to those of high tension power transmission lines. It is likely in some way, by means of microwave cables, that television signals will be transmitted between large centers, which soon will permit the display of all important events to be followed on the receiver screens at home at the same time they occur."

The second option proposed by Clavier, closely spaced towers, has not been adopted, since it undoubtedly was not the most economical at the time the infrastructure of the long distance network had to be installed, i.e., at a time when the transmission capacities were low.

Frequencies above 12 GHz cannot be used in the existing national infrastructure, since higher frequency waves are absorbed by rain and, to limit the cutoff time due to spreading, the length of the jumps must be reduced.

In France, the existing microwave beams at 13 and 15 GHz have been installed in local and possibly regional networks, with 15 to 30 kilometer jumps. The 19 GHz band could be used to extend major microwave trunks in an urban zone. The lengths of these communications links, which possibly include several jumps, would not generally exceed 10 to 20 kilometers.

Curve c in Fig. 2 gives the maximum range of a microwave jump, when it is desired to ensure an annual cutoff time of 12 s/km (CCIR specification) with a system which has a 40 dB fading margin available under average climatic conditions (the Paris Region for example). This range decreases very quickly with frequency.

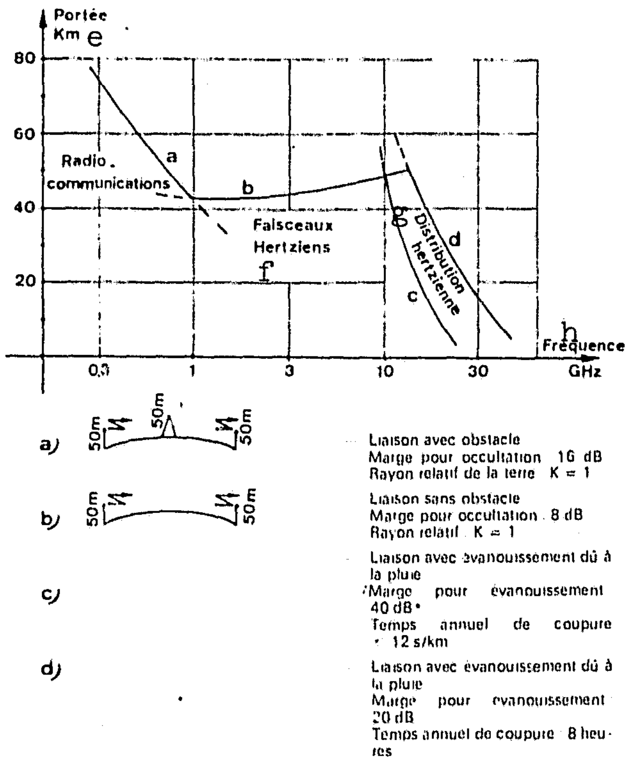


Fig. 2. Range of microwave transmission.

Key:
- a. Communication with obstacle, occultation margin 16 dB, beam relative to ground K=1
- b. Communication without obstacle, occultation margin 8 dB, relative beam K=1
- c. Communication with fading due to rain, fading margin 40 kB, annual cutoff time <12 s/km
- d. Communication with fading due to rain, fading margin 20 dB, annual cutoff time 8 hours.
- e. Range, km
- f. Microwave beams
- g. Microwave distribution
- h. Frequency, GHz

To reduce the cost of the line of a millimeter microwave beam channel, an attempt can be made to increase the transmission rate as much as possible. Thus, at 29 GHz the utilization of a microwave beam at 800 Mbit/s per channel with 1 kilometer jumps has been considered [4]. The equipment developed in this way was very similar to circular waveguide equipment.

## 3.2. Microwave Distribution

Another radically different approach, based on very light equipment, has appeared at a time when talk /38
has begun of millimeter voice carriers and millimeter wave binocular radios for noncivilian applications [5, 6].

Why not attempt to perfect simplified equipment to bring into being distribution lines for subscriber connections, not just lines for the transmission network? It then is a question of reducing the most costly functions to their simplest expression: transmission-receiving duplexing; channel filtering; oscillator frequency stabilization; transmission amplification, etc. This simplification effort is possible on condition of appropriating relatively large frequency bands to these light systems.

In addition, there can be much greater tolerance towards cutoffs due to rain in subscriber networks. The annual cutoff time target will be several hours per connection, regardless of distance. Curve d in Fig. 2 gives the maximum range of a microwave distribution line, when an annual cutoff time of less than 8 hours ($10^{-3}$ of the year) should be guaranteed for a connection with a system which has a 20 dB fading margin. Thus, the ranges are much larger for microwave distribution, even with simplified equipment, than for microwave beams.

Millimeter waves could rapidly appear to be particularly appropriate for microw e distribution in a country like France, where a "frequency shortage" begins to be felt in the decimeter and even centimeter wave range. Microwave transmission then will be divided into three large techniques, each of which corresponds to an appropriate frequency area (see Fig. 2):

below 2 GHz. Radiocommunications. Single line connections, essentially for mobile communication with possible occultation of the radio path by obstacles;

from 2 to 20 GHz. Microwave beams. Multiplexed connections at medium to long distance with visibility and a heavy infrastructure;

above 20 GHz. Microwave distribution. Lines from a point (central) to several points (subscribers or groups of subscribers) with visibility and a light infrastructure.

Microwave distribution now is a rapidly growing technique. Up to now, subscriber connections by radioengineering line have been made with 150 and 400 MHz single line equipment. More than a thousand subscribers located in a mountainous zone and on coastal or river islands have been thus connected to the PTT network. In addition, a complete microwave distribution system is in development at 1.5 GHz. It will permit connection of 15 subscribers by small groups

with a single carrier, and with the telephone lines digitally coded with multiple time distribution access (AMRT).

These various systems are especially appropriate for developing countries, where the subscribers frequently are very distant from the telephone exchanges. On the other hand, their possibilities are limited in France, since the VHF and UHF bands are given priority assignment to mobile communications.

For subscriber connections at a higher rate (new services at 64 kbit/s and below, video, etc.), higher frequencies must be resorted to, and microwave distribution should be required for cable distribution (optical fibers eventually) in the following cases:

subscribers located in zones which are difficult to reach;

temporary connections and special rapidly developing networks (extension of digital transmission networks by satellite, etc.);

subscribers for whom very good connection security must be ensured (diverse routing).

### 3.2.1. Principal Characteristics of 31 GHz Microwave System

The first 31 GHz system is being developed [7, 8]. It will permit establishment of digital communications at a rate of 704 kbit/s, and it will therefore be well adapted for connection of groups of no more than ten subscribers.

The millimeter transmission-receiving structure is especially simplified, some functions (transmission-receiving duplexing, the frequency operating mechanism) having been shifted to an intermediate frequency or to the base band.

This thus causes the use of a completely standard "millimeter headset," which can be used for other applications such as Doppler radar.

The technical options are the following:

a single oscillator for transmission and reception;

direct frequency modulation of the oscillator;

frequency drift of the oscillator, which can reach $10^{-3}$ in the actual environment.

The oscillator is a Gunn diode oscillator tuned by a varactor to /39
which the modulation of the transmission is applied. The receiver mixing circuit is distinct from the oscillator, and it includes a single diode mixer. The oscillator and the mixer are coupled by a circulator. The intermediate frequency amplified signal carries both the transmission and receiving modulations. A circuit called "anti-local" is located in the base band to cancel the transmission modulation and reconstitute the digital signal received. Finally, an automatic frequency control circuit is set up at only one of the two ends to stabilize the intermediate frequencies (Fig. 3).

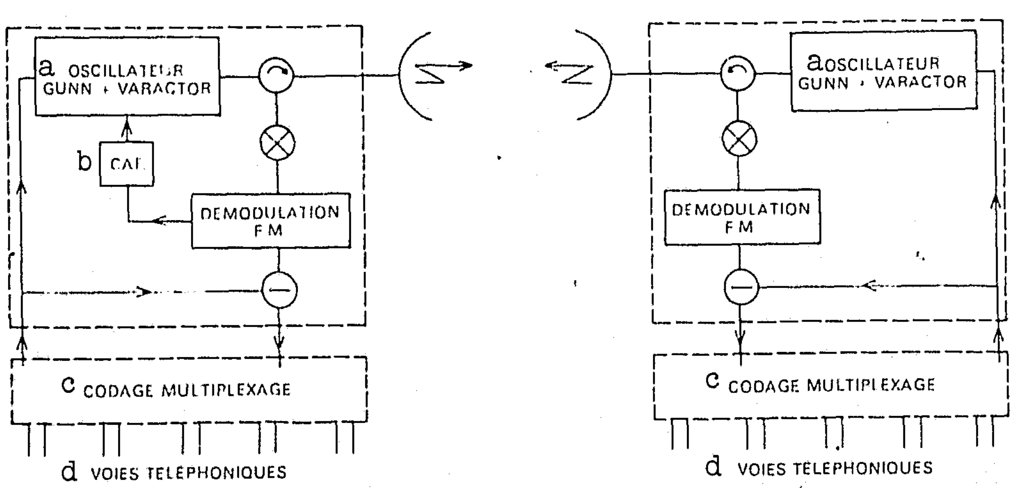


Fig. 3. Block diagram of communication link.

Key: a. Gunn oscillator + varactor
b. Automatic frequency control
c. Coding-multiplexing
d. Telephone lines

Under these conditions, the millimeter headset is reduced to an oscillator-mixer without a strong overvoltage cavity or millimeter filter. Of course, such a solution can only be considered in the case of low digital rates on the order of a few hundred kbit/s.

The transmitter-receiver is generally characterized numerically by the gain of the system, which indicates the ratio of the transmission power to the threshold receiving power for which the error rate exceeds the limiting error rate. This gain exceeds 90 dB from the time when the noise factor is below 15 kB for a rate of 704 kbit/s.

Another important characteristic is the frequency band occupied by a channel. For this system, with the two directional transmission taken into account, it is on the order of 100 MHz, with allowance for a maximum drift of 30 MHz of the millimeter oscillators and the necessity for protecting reception against interference at the frame frequency.

### 3.2.2. Lannion-Tredrez Experimental Line

A 9.5 kilometer long experimental line was installed at Lannion at the end of 1979. It permitted the joining of two subscribers to the CNET exchange in actual traffic.

The millimeter amplifier of the subscribers, which includes all the transmission and receiving circuits, was placed at the top of a quite standard 12 meter high metal post. Under these conditions, the isolation of the radio path from trees and structures is only a few meters at several connection points, which is quite enough.

Antennas 30 centimeters in diameter with 35 dB gain were placed at each end of the communication line. Aiming them was easy, and the fading margin then was 18 dB. During nine months of measurements, the cumulative cutoff time due to rain was 148 minutes, or less time than the four hours anticipated for average climatic conditions, in the Paris region for example.

These 148 minutes correspond to 48 cutoffs, the duration distribution of which is shown in Fig. 4. The average cutoff duration is 3 minutes. Such cutoffs are thus rarely repeated and at the same time not too long, which should be favorable from the point of view of transmission quality.

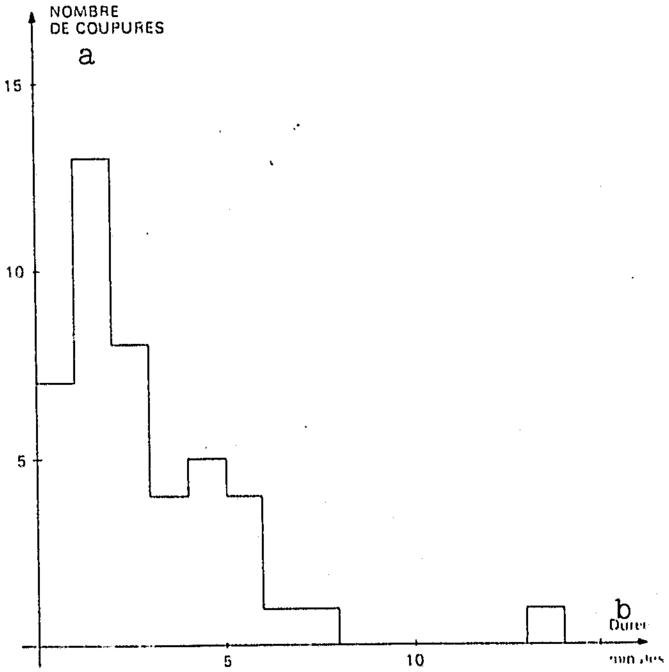


Fig. 4. Histogram of Lannion-Tredrez link cutoffs, 1980.

Key: a. Number of cutoffs
b. Duration, minutes

### 3.2.3. Prospects of 31 GHz System

This system operates at a nominal rate of 704 kbit/s, which corresponds to a digital /40 rate of the subscriber network in the course of standardization. It can easily be adapted to rates from a hundred kbit/s to 2 Mbit/s at least. Figure 5 shows the area of use of this system. Curve a corresponds to the maximum range with 30 centimeter diameter antennas, for an annual cutoff rate of $10^{-3}$. For greater distances, existing 2 and 15 GHz systems must be used. Curve b gives the maximum range of a digital transition over a conventional symmetrical paired cable without intermediate repeaters. The addition of repeaters permits an increase of this range (curve c with one repeater), but it makes the installation and operating costs (remote power supply, etc.) increase in a nonnegligible way.

This first 31 GHz millimeter system remains a point to point system. To join several groups of subscribers in the same zone from a central point such as a PTT tower, several millimter communication lines can easily be installed at the same frequency, with angular

shielding from the antennas on the order of approximately 30 decibels.

The time engineering which associates transmission and digital concentration must quickly be resorted to. In particular, the time distribution multiple access technique (AMRT) could be used. It is already used for microwave distribution systems, at 1.5 GHz in France and in a special band from 10.5 to 10.68 GHz in the United States, to extend digital satellite transmission networks [9, 10].

## 4. Space Transmission

### 4.1. Evolution of Space Transmission

Satellite communications were first used for intercontinental transmission of telephone lines and television channels. Their use is now considered very broadly for data transmission and video transmission to one or more countries in limited geographic areas [11].

The diversification of satellite communications has made necessary the use of higher frequency bands than the 4 and 6 GHz bands initially used. The 11 and 14 GHz bands have been the subject of thorough experiment, especially within the framework of the European OTS program. Several telecommunications networks have been defined in this band (ECS-Telecom 1), and they should rapidly become operational.

The 20 to 30 GHz band then was the subject of experiments, but numerous uncertainities delay its use.

### 4.2. Transmission at 20 and 30 GHz

The use of higher frequencies in microwave transmission is made possible by shortening the microwave jumps.

In the area of space, from the time when geostationary satellites, there obviously no longer was the question of working on path length . . . The antenna gain must be increased to preserve the same trans-

mission capacity.

This increase in gain is calculated in Table II with the following hypotheses:

the type of transmission (rate, modulation) is the same in different bands;

the path considered is the downward path, i.e., at 4, 11 and 20 GHz, since it is generally the path most disturbed by propagation fading. These interfere at the same time with the reception noise temperature and losses in space;

the transmission /41
power aboard the satellite is connected with the constraints of dissipation and useful charge consumption and not with frequency. Under these conditions, it can be considered that it is the same at different frequencies;

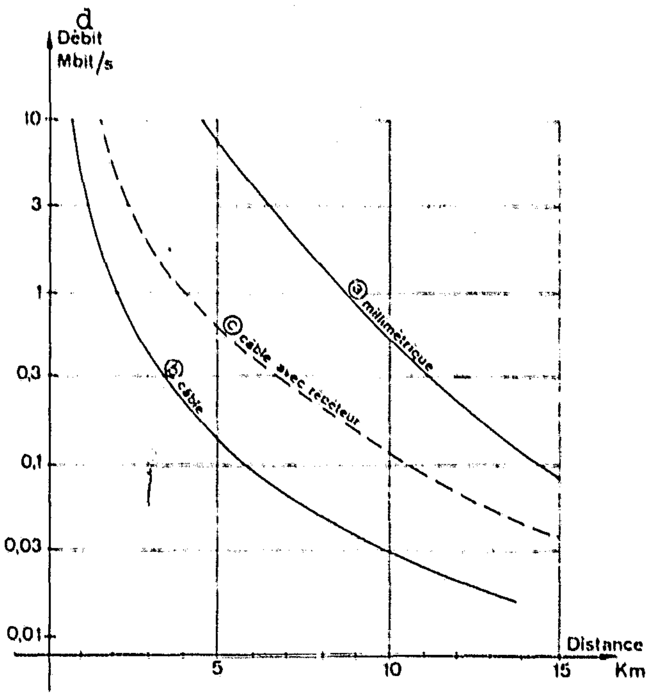


Fig. 5. a. Range of 31 GHz link (system gain 90 dB at 700 kbit/s); b. Range of symmetrical pair cable link without repeater; c. Range of cable link with one repeater.

Note: The direct line distance for the cables is concerned, i.e., 0.66 times the actual length of the cable.

Key: a. Millimeter
b. Cable
c. Cable with repeater
d. Rate, Mbit/s

the margin to be taken into account for propagation fading due to rain depends at the same time on the geographic location of the earth station, the angle of inclination of the space path and the cutoff time target, which becomes an important parameter of transmission availability at elevated frequencies. Two extreme cases are considered with an angle of inclination of approximately 30 degrees.

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TABLE II

| a Trajet descendant (Référence : transmission 4-6 GHz) | | 11/14 GHz | 20/30 GHz | |
|---|---|---|---|---|
| | | | b Région parisienne/5.10$^{-4}$ de coupure | c Littoral méditerranéen/10$^{-4}$ de coupure |
| – Puissance émission d | dBm | – | – | – |
| – Facteur de bruit récepteur e | dB | – 1 | – 3 | – 3 |
| – Rapport signal à bruit f | dB | – | – | – |
| – Pertes espace libre g | dB | – 9 | – 14 | – 14 |
| – Marge pour évanouissement de propagation h | dB | – 3 | – 8 | – 23 |
| – Gain de l'antenne de la station terrienne i | dB | + 3 | + 6 | + 6 |
| Déficit à compenser par l'augmentation du gain de l'antenne j satellite | dB | 11 | 22 | 37 |

Key: a. Descending path (reference 4-6 GHz transmission)
b. Paris region/5.10$^{-4}$ of cutoff
c. Mediterranean coast/10$^{-4}$ of cutoff
d. Transmission power
e. Receiver noise factor
f. Signal to noise ratio
g. Open space loss
h. Spread fading margin
i. Ground station antenna gain
j. Deficit to be compensated by increase of satellite antenna gain

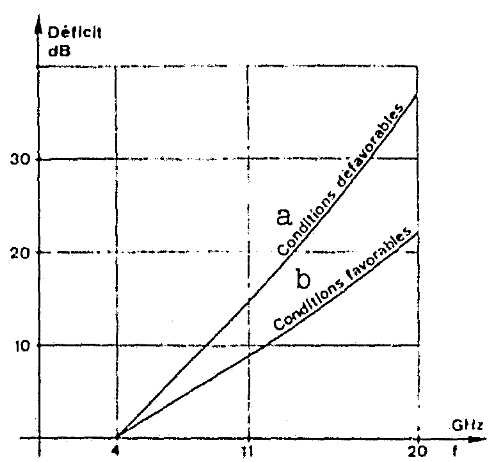


Fig. 6. Descending path deficit to be compensated vs. frequency.

Key: a. Unfavorable conditions
b. Favorable conditions

Compensation of additional propagation losses by an increase in gain of the onboard antennas leads to a very strong reduction of the radiation beams of the satellite. For a high capacity transmission, an aperture angle of approximately 10 degrees must be allowed in the 4/6 GHz band and an angle of 0.6 degrees in the 20/30 GHz band. The area covered by a beam with such an aperture angle would be approximately 100,000 km$^2$. More than six beams would be required to cover all of France.

Putting narrow beam antennas into operation would normally lead to the addition of supplementary circuits to the useful load of the

satellite. Better antenna stabilization must first be ensured, possibly by the addition of an automatic tracking circuit. Beam switching could then be introduced, which is of particular concern when the number of beams is large.

The installation of a transmission power control circuit in ground stations, which permits its reduction outside of fading periods, should turn out to be necessary to reduce interference between systems. Finally, the diversity of locations, i.e., reception at two neighboring ground stations situated at a sufficient distance apart, would turn out to be of concern in the event of unfavorable conditions (strong rainfall intensity, very severe cutoff time target).

### 4.3. Intersatellite Communications

In addition, the establishment of direct communications between satellites is considered, in particular to suppress intermediate reflection on the ground in the case of communication established with two satellites.

Millimeters waves are quite well adapted to this type of application, when there obviously no longer is a question of absorption due to rainfall in this case. The use of frequencies around 60 GHz was formerly considered. Finally, during the last World Radio Communications Conference, it was decided to allocate, in addition to the 54-58 and 59-64 GHz bands, two lower frequency bands: 22.5-23.5 GHz and 32-33 GHz. The production of transmission-receiving equipment is easier in these last two bands. Meanwhile, it remains to be proven that the division of these bands with other services, radionavigation in particular, does not create intersurmountable constraints.

## 5. Mobile Communications

### 5.1. The Principal Applications

Ground millimeter communications can only be short range commucations, since they must only be accomplished with direct visibil-

ity or under conditions very close to direct visibility. For this reason, they are allocated to the case of steered moving vehicles, i.e., moving vehicles which should follow a determined course. This is the case of trains, subway branches, motor vehicles on highways, barges on the canals and ships in a channel.

Millimeter communication should permit the development of high rate communications up to 1 Mbit/s and beyond, which hardly can be achieved in VHF-UHF. To ensure continuous communications on a long distance transport line, fixed transceivers must be laid out one to two kilometers apart along it. The radio beam in which the millimeter waves are concentrated is very narrow. Thus, a kind of millimeter tube is obtained in which the moving vehicle travels.

In the millimeter wave range, it would appear that the effect of multiple paths would be reduced and that propagation would remain accurate, even in tunnels, on bridges, along real property, etc., not only in a straight line, but also in the presence of some curves.

Several systems are being studied for continuous communications /42 with trains at 30 GHz [12] and 60 GHz [13], as well as for point communications at 60 GHz between cars and highway entrances [14].

## 5.2. Optimization of Frequency for Communication with Trains

The use of frequencies on the order of 60 GHz could present several advantages over lower frequencies on the order of 30 GHz:

the effect of multiple paths would be less;

the absorption of 60 GHz waves by the oxygen of the air greatly limits interference between two different sections; thus, it is much easier to reuse the same frequency along a line, and frequency stabilization of the millimeter oscillators could possible be simplified;

the installation of a space difference system on the moving

vehicle (30 centimeters phase difference at 60 GHz) would prove to be easier.

These advantages obviously pay off in a large decrease in spacing between two fixed transceivers [13], which would be only 1 kilometer instead of 2 kilometers at 30 GHz.

## 6. Conclusion

The development of millimeter waves for civilian communications has been retarded up to now, especially because the needs of high capacity transmission have not been strong enough to justify the installation of circular waveguides in a long distance network.

But this situation should evolve for 20 to 60 GHz transmission in open space, which makes available great advantages:

it is a question of available bands of sufficient width to permit the relaxation of some constraints, such as frequency stabilization and microwave filtration;

the equipment, the antennas in particular, can be compact, which makes their installation easier, without a heavy infrastructure, close to subscribers and even on moving vehicles;

interference between communications lines will be limited for at least three reasons: the radio paths are close to the ground, the attenuation of millimeter waves due to obstacles is large, and the high directivity of the aerials restricts the radiation zones.

On the contrary, the range of horizontally propagated millimeter waves (or the coverage zone of space transmission) remains reduced, because of attenuation due to rainfall and nearly optical visibility without occultation is required.

Finally, all these elements, including the range limitations due

to rain and the visibility constraints, except for some satellite transmissions, contribute to research on so called "full broadcasting" or "bottom of the range" applications, i.e., in the distribution network for fixed or mobile subscribers.

Of course, there are still new technologies to be perfected, the most promising eventually being "monolithic integration," to obtain large reductions in the cost of equipment and thus permit these millimeter systems to be competitive.

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